Evolution of the Marginal Ice Zone: Adaptive Sampling with Autonomous Gliders

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LONG-TERM GOALS

This study contributes to long-term efforts toward understanding:

- Ocean-ice-atmosphere dynamics that impact sea ice evolution.
- The impacts of Arctic change on sea ice and on the dynamics of the upper ocean.

OBJECTIVES

The Seaglider program focuses on:

1. Characterizing vertical structure (temperature, salinity, density), internal wave variability, turbulent mixing, and radiative warming as a function of distance from the ice edge, extending from open water into full ice cover.
2. Understanding the balance and interplay of processes that supply freshwater and heat to the ice-ocean boundary layer (sea ice melt, radiative heating, wind-driven mixing, internal waves and small-scale, wind stress curl-driven vertical exchange) and how this varies with ice cover.

Within the MIZ, the mix of ice and open water, combined with variations in ice surface and keel roughness, lead to a complex balance of processes that varies over short spatial and temporal scales. Radiative heating and buoyancy input from melting sea ice act to stratify the surface layer, while wind-driven mixing, internal wave sheer and wind-induced vertical circulation conspire to deepen it. Heat input to the ice-ocean interface stems from lateral advection, radiative heating and, possibly, entrainment (through diapycnal mixing and vertical advection) of warmer water from below. Moving away from the MIZ into ice-free waters, the balance of processes should shift toward those expected in the open ocean, modulated by the surfeit of surface freshwater left by the retreating sea ice. Moving in the opposite direction, away from the MIZ into fully ice-covered waters, we anticipate that internal wave variability, mixing and vertical exchange will weaken toward the levels previously observed in the ice-covered Arctic.

APPROACH

The MIZ intensive field program employed a broad array of autonomous platforms to characterize the processes that govern Beaufort Sea MIZ evolution from initial breakup and MIZ formation though the

course of the summertime sea ice retreat. Instruments were deployed on and under the ice prior to initial formation of the MIZ along the Alaska coast, sampling though the melt season as they drifted westward and the ice retreated northward. An array of long-endurance, autonomous Seagliders followed the retreating ice edge to document upper ocean structure and quantify the relative importance of processes that impact the ice-ocean boundary layer in and around the MIZ. Specifically, the glider surveys:

- Collect observations that span open water, the MIZ and full ice-cover.
- Resolve the short temporal and spatial scales associated with key upper ocean processes.
- Quantify how the dominant upper ocean processes vary as a function of location relative to the MIZ.
- Measure turbulent mixing rates (via micro-temperature) in the upper water column.
- Measure multi-spectral downwelling irradiance in the upper water column.
- Provide high-resolution spatial context for other components of the DRI.

Long-endurance, autonomous Seagliders have been adapted for extended missions in ice-covered waters, where they provide several unique capabilities. Ice-capable Seagliders can maintain persistent (many months) sampling under full ice cover, providing excellent (kilometers) spatial resolution and collecting measurements within meters of the critical but hazardous ice–ocean interface. Moreover, Seagliders can readily transition between full ice cover and open water, including routine operation in the difficult-to-access marginal ice zone. When operating in ice-covered waters, gliders navigate by trilateration from acoustic sound sources (or dead reckoning should navigation signals be unavailable) and incorporate enhanced autonomy to perform functions such as sensing overhead ice, determining when to attempt to surface and decision making in the event of lost navigation or instrument malfunction.

WORK COMPLETED

Four Seagliders were deployed at the shelf break off Prudhoe Bay, AK, on 28 July 2014, from the R/V Ukpik. After deployment, the gliders transited north along two parallel lines, reaching the ice edge after one week. All for gliders did several sections from the open ocean, through the marginal ice zone, to the fully ice-covered ocean (Fig. 1). The gliders occupied about 15 sections across the ice edges, penetrating as far as 75°20'N. Gliders were all under the ice for most of September, emerging to the open water only in the last week of September before recovery on 02 October 2014.

The Seagliders carried turbulence sensors, measuring small-scale temperature fluctuations. Two of the MIZ gliders also carried sensors to measure small-scale velocity fluctuations, the first time that this system has been used on Seaglider in the open ocean. The system provides real-time estimates of rates of dissipation of thermal variance (χ) and kinetic energy (ε). Gliders also sampled dissolved oxygen, optical backscatter (chlorophyll and CDOM fluorescence) and multi-spectral downwelling irradiance. Careful calibration casts, including water sampling, were conducted during both the deployment and recovery cruises.

An example of a section from the ice to the open water, occupied in early September by sg197, is shown in Fig 2. Temperature and salinity sections show a strong front at the ice edge, where cold and fresh water meets warmer water in the ice-free portion of the section. Also note the broadening of the isopycnals near 50-m depth at the ice edge. This feature, presumably due to ice-edge mixing, appears to be present in all glider sections. We also note a distinct change in the signature of the Pacific

Summer Water, the warm water mass near 60 m – it appears to be more diffuse in the ice-free region relative to the ice-covered part of the section.

In order to navigate and calculate their position under ice, gliders need to accurately know the acoustic navigation source positions and travel time of the acoustic signals. In collaboration with Frietag's group at WHOI, an acoustic navigation network was built and deployed during the MIZ program. Broadband sources encoding data onto the signal were used, allowing the sources to transmit position. Instruments hearing the signals can therefore navigate from mobile (drifting) sources, unlike if older RAFOS navigation sources were used.

RESULTS

Early exploration of glider-based sections through the marginal ice zone reveal strong fronts where cold, ice-covered waters meet waters that have been exposed to solar warming, and O(10 km) scale eddies near the ice edge (Fig. 2). In the pack, Pacific Summer Water and a deep chlorophyll maximum form distinct layers at roughly 60 m and 80 m, respectively, which become increasingly diffuse as they progress through the MIZ and into open water (Fig. 3). The isopynal layer between 1023 and 1024 kgm^{-3}, just above the PSW, consistently thickens near the ice edge, likely due to mixing or energetic vertical exchange associated with strong lateral gradients in this region. Sections across the ice edge just prior to recovery, during freeze-up, reveal elevated chlorophyll fluorescence throughout the mixed layer (Fig. 4). This is consistent with a secondary phytoplankton bloom fed by nutrients entrained into the euphotic zone during overturning associated with cooling and brine rejection during freeze-up.

The new broadband acoustic navigation system achieved 400+ km range within the narrow sound channel at roughly 150-m depth formed by the warm Pacific Summer Water, with shorter, 100-km range through the rest of the water column, outside the channel (Fig. 5).

The recovery cruise at the end of September 2014, on R/V *Norseman II,* provided us with an opportuinity to conduct over two days of very high-resolution sampling of the region near the ice edge (Figure 6). Sections of temperature and salinity extending from the ice edge roughky 15 km into open water sampled by the Underway CTD on 2 October, 2014 provide an example (Figure 7). Profile spacing ranges from about 200 m near the ice to a little under 1 km further away. A time series of sections (not shown) was collected to capture the time evolution of the sharp temperature-salinity front that marks the ice edge. The sections also reveal thickening of the 22-23σ_θ density layer, above the location where the signature of the Pacific summer water (water with T>0°C near 60m) disappears.

IMPACT/APPLICATION

None yet, though the light-weight approach used for aviation and ice camp operations has attracted considerable interest, as has the use of integrated systems of autonomous instruments for Arctic observing. we anticipate that results from this program will contribute to improvements in how numerical simulations deal with sea ice evolution, while technological developments in under-ice gliders and acoustic navigation may have significant impact on our ability to collect long-term measurements in ice-covered waters.

RELATED PROJECTS

Multiple efforts within the Office of Naval Research Marginal Ice Zone Program. This includes projects directed by principal investigators Freitag, Hwang, Maksym, Maslowski, Owens, Stanton, Thomson, Timmermans, Toole, Wadhams, Wilkinson and Zhang.

The underway CTD sampling of the ice-edge during the recovery cruise, executed in conjunction with surface wave and surface turbulence measurements with J. Thomson's group, led to a grant to Rainville to send instruments to R/V *Sikuliaq* to augment upper ocean sampling capabilities during the SeaState DRI field campaign (October 2015).

PUBLICATIONS

Lee, C.M., S. Cole, M. Doble, L. Freitag, P. Hwang, S. Jayne, M. Jeffries, R. Krishfield, T. Maksym, W. Maslowski, B. Owens, P. Posey, L. Rainville, B. Shaw, T. Stanton, J. Thomson, M.-L. Timmermans, J. Toole, P. Wadhams, J. Wilkinson, and Z. Zhang, 2012. Marginal Ice Zone (MIZ) Program: Science and Experiment Plan, Technical Report APL-UW 1201. Applied Physics Laboratory, University of Washington, Seattle, September 2012, 48 pp.

FIGURES

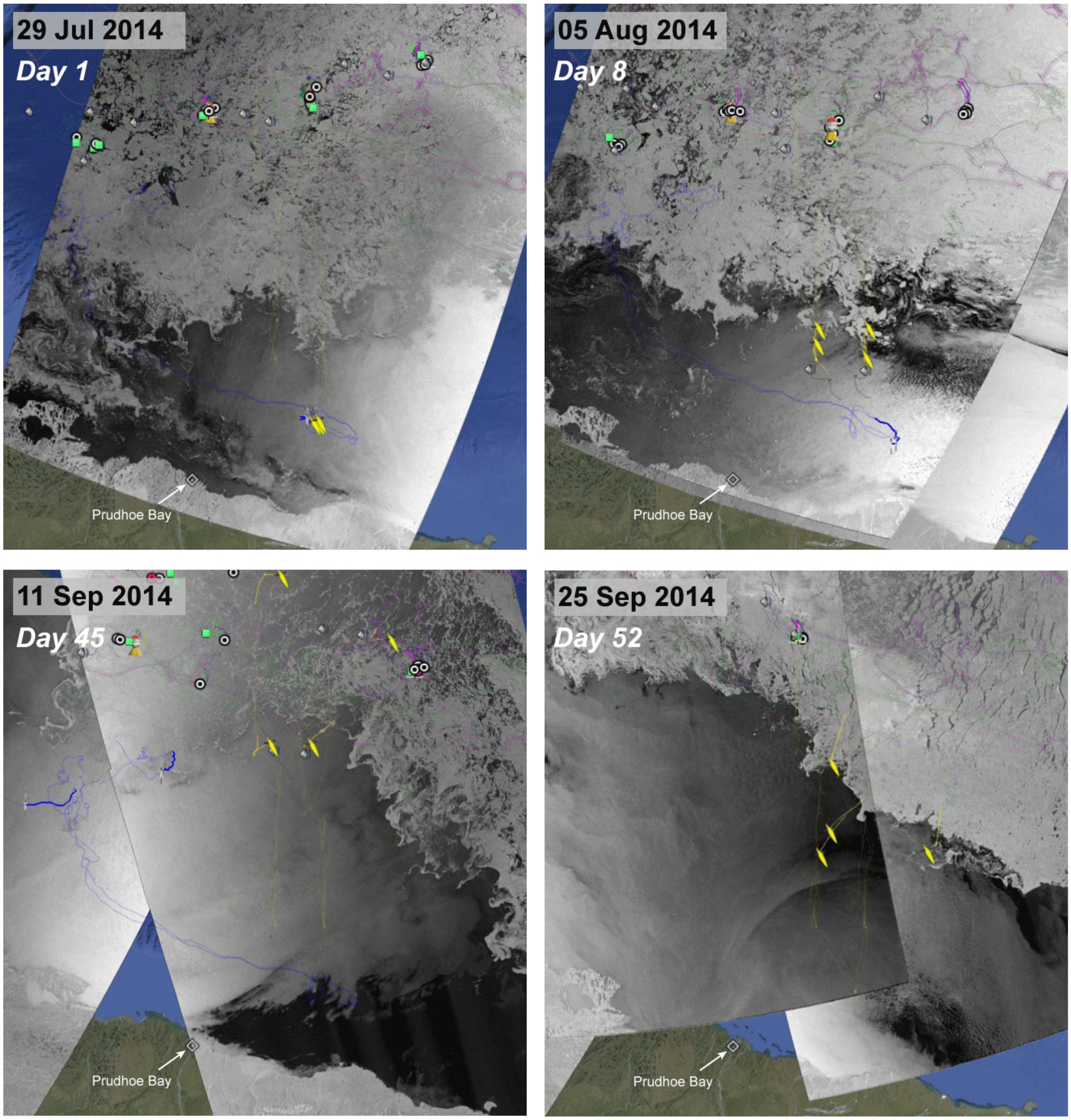

***Figure 1**. Glider positions at selected times during the three-month deployment. Yellow icons mark glider locations, while other symbols indicate the positions of Ice-Tethered Profilers, Autonomous Ocean Flux Buoys, Ice Mass Balance Buoys and Wave Buoys. Radarsat SAR imagery plotted in the background depicts ice cover, with black indicating open water. Dates and number of days into the mission are indicated in the upper right corner of each panel.*

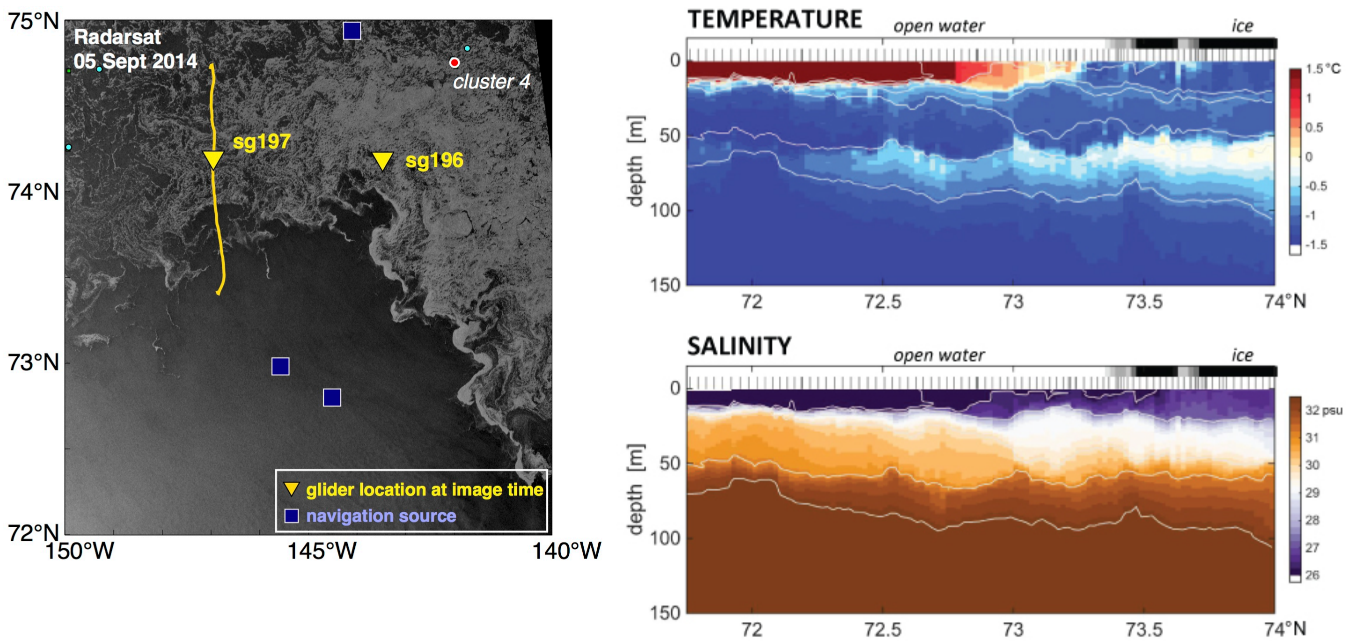

***Figure 2**. Example of a glider section from the ice to the open water, from sg197 in early September 2014. Ice edge is defined here as the 30% ice concentration, estimate from near-real time satellite microwave product. Temperature and salinity sections (right), with potential density contours (1 kgm^{-3} intervals) show a strong front at the ice edge, where cold and fresh water meets warmer water . Also note the broadening of the isopycnals (white lines) near 50m at the ice edge (between 73°N and 73.5°N).*

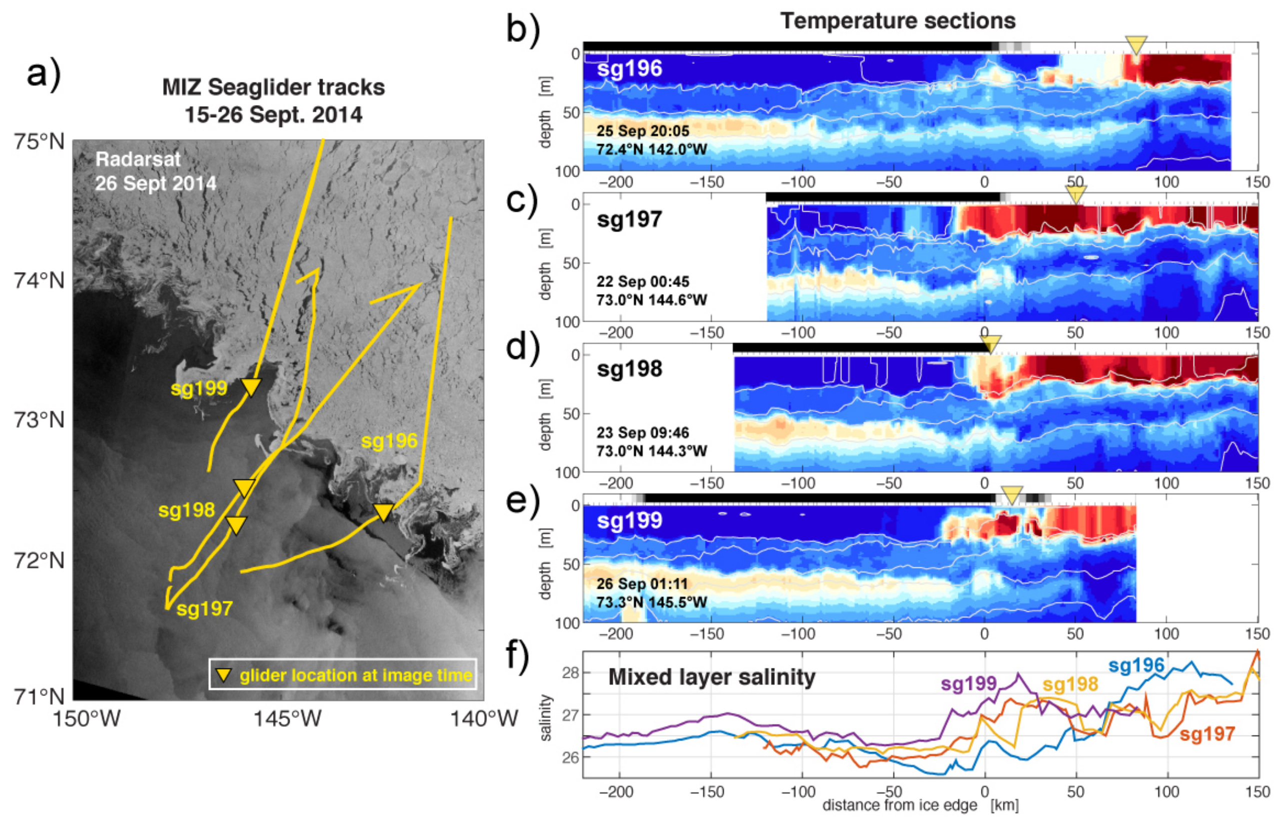

Figure 3. (a) Tracks of the 4 MIZ gliders as they exited the ice pack at the end of September 2014. (b-e) Temperature as a function of temperature and distance from the ice edge. The presence of ice indicated by the black line on top of each panel. Location of each glider at the time of image is shown by a triangle. (f) Salinity of the surface mixed layer as a function of distance along each of these sections, showing variations both under the ice and in open water, with highest variance near the ice edge.

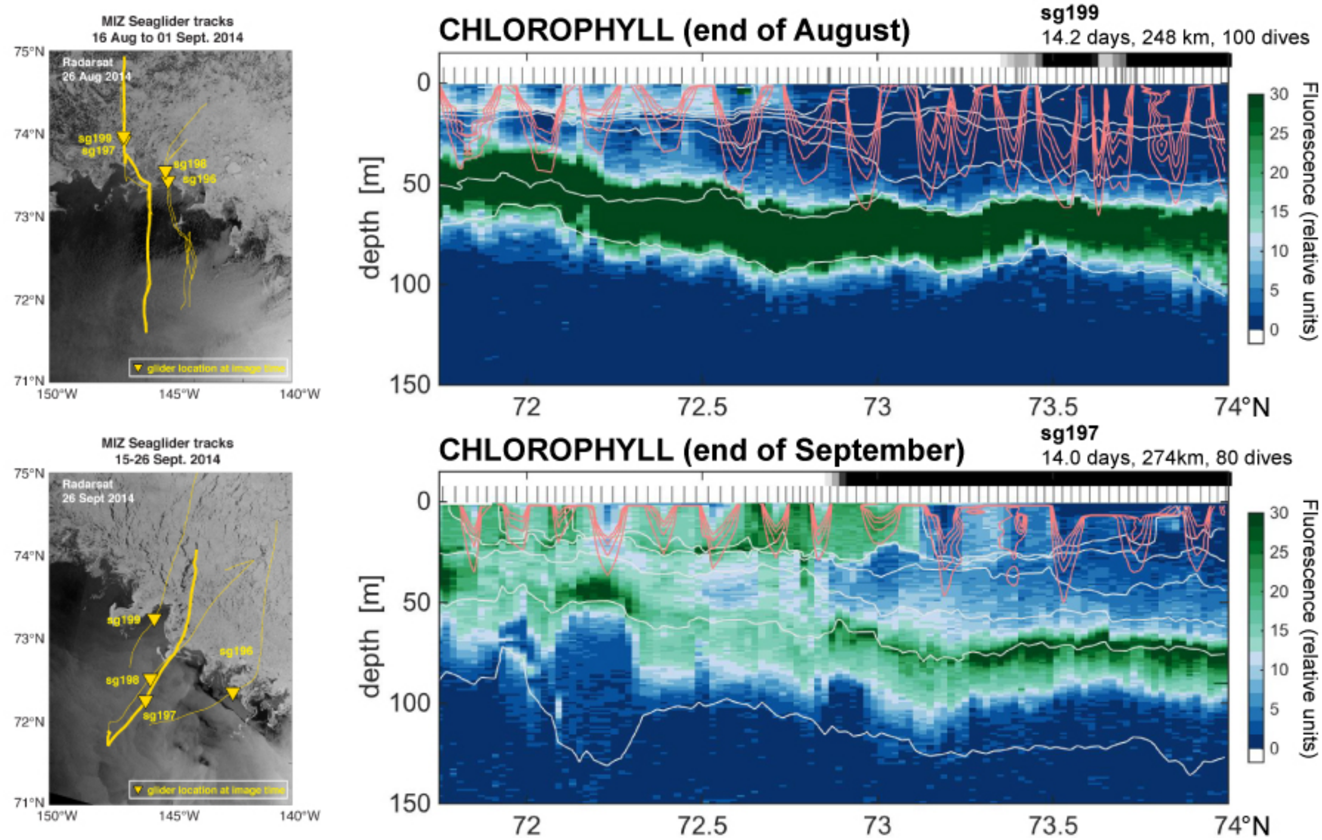

Figure 4. Chlorophyll fluorescence sections from the end of August (top) and the end of September (bottom). During summer, a subsurface chlorophyll maximum exists at roughly 60 m, associated with the Pacific Summer Water. During autumn freeze-up, the subsurface maximum persists in the ice-covered regions, but within the MIZ, and in areas of open water, sections reveal elevated chlorophyll concentrations throughout the mixed layer. Concentrations appear to be too large for to be explained simply by redistribution of phytoplankton from the subsurface maximum. The chlorophyll signature is consisted with the presence of a secondary bloom, associated with nutrients brought from below the mixed layer by overturning due to cooling and brine rejection. Black lines on top of sections indicate the presence of sea ice. Red lines are contours of downward solar radiation.

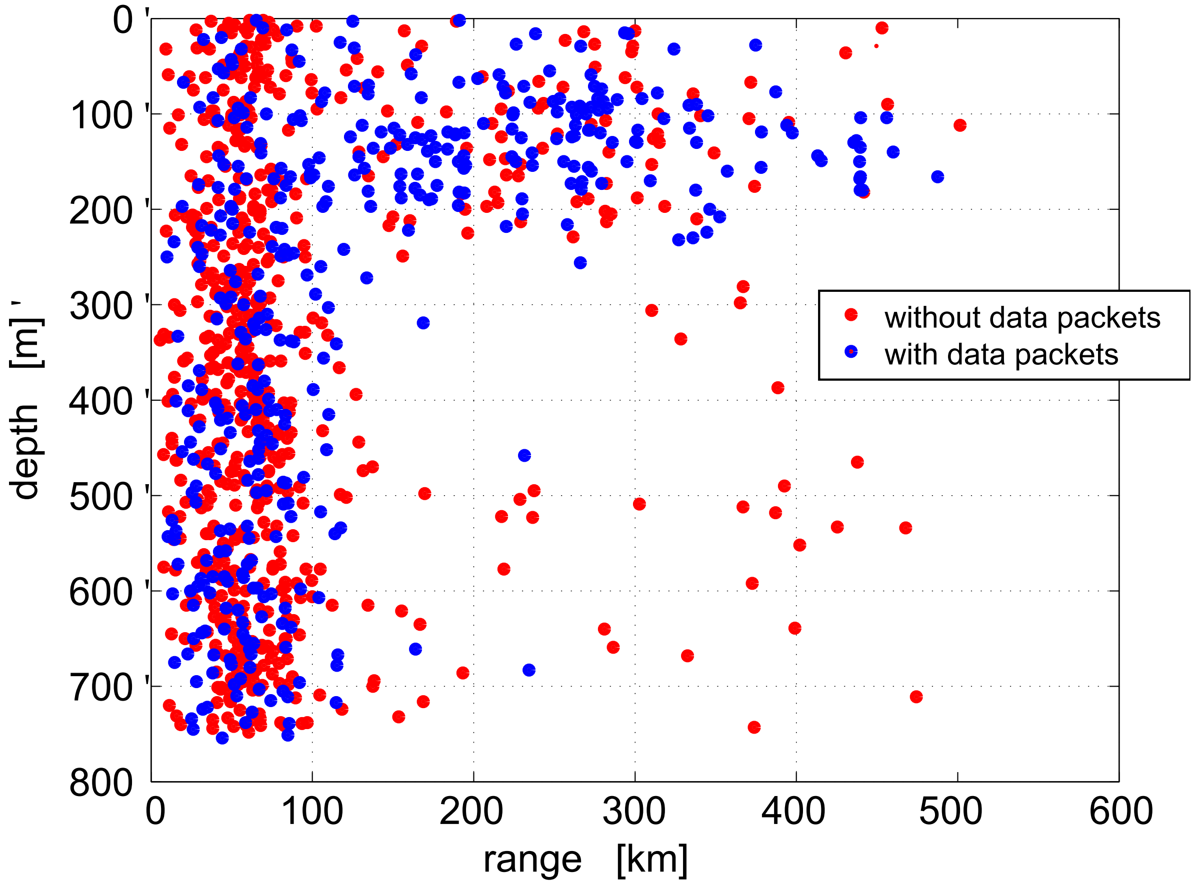

***Figure 5**. Glider acoustic navigation receptions as a function of horizontal range and depth. Blue marks indicate receptions with decodable data packets. Red marks indicate receptions for which the data packet could not be decoded. Although gliders cannot calculate range in real time from these receptions, the data can be used for geolocation in post processing.*

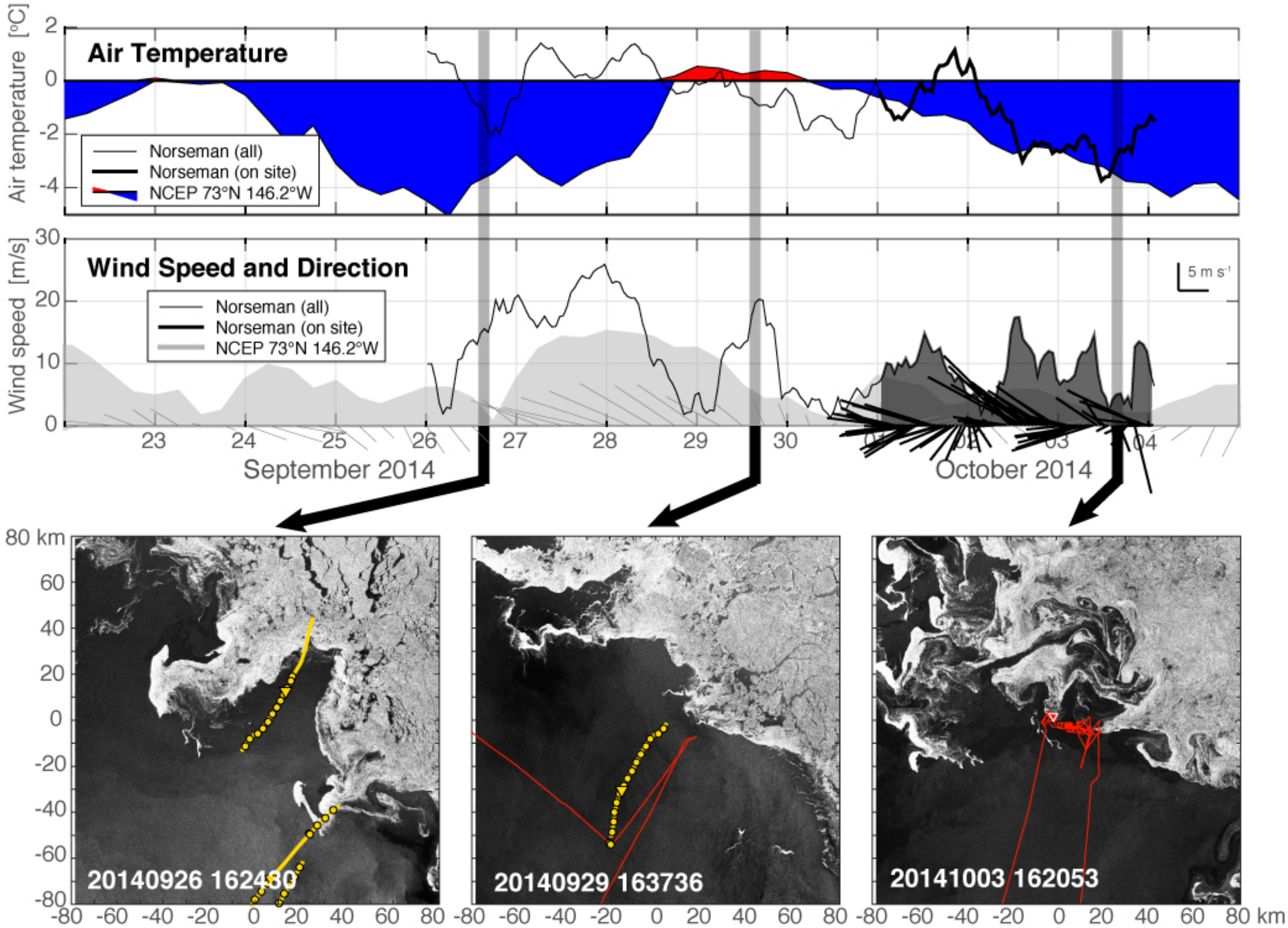

Figure 6. Time series of air temperature (top – freezing showing in blue) and wind speed and direction (central panel), both from NCEP reanalysis at the ice edge (73°N 145°W) and recorded from R/V Norseman during the recovery cruise. Satellite SAR images at representative times during the ice edge sampling are shown on the bottom row, along with glider (yellow, surfacing shown by circles) and ship (red) tracks. Tracks are shown +/-2 days from the time of the image. Locations of gliders or ship at the time of the image are shown with triangles.

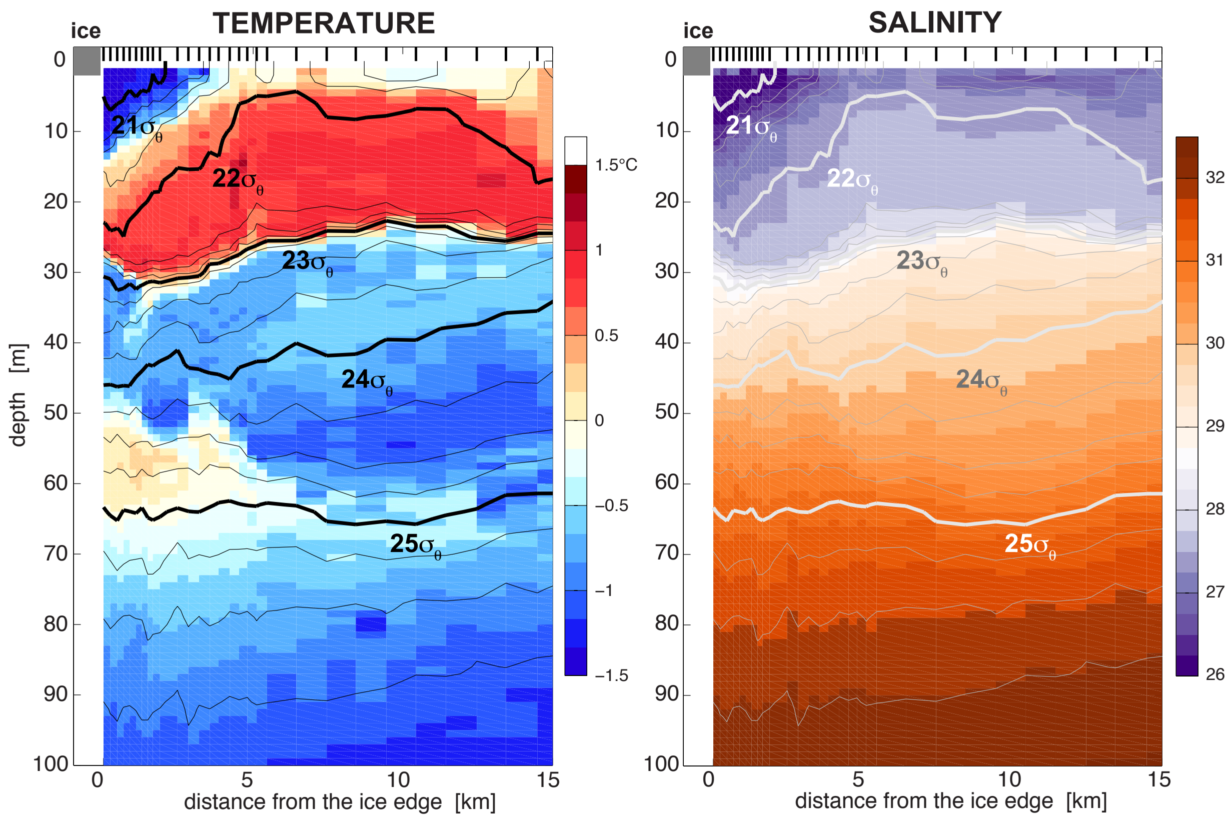

Figure 7. *Temperature and salinity from the ice edge to about 15 km, sampled by the underway CTD during the Norseman II cruise (02 Oct 2014). Profile locations (36 casts) are indicated on the top axis. Potential density is contoured. Note the sharp temperature and salinity front near the ice edge, as well as the broadening of the 22-23σ_θ density layer above the location where the signature of the Pacific summer water (water with T>0°C near 60m) disappears, 5-10 km from the ice edge.*